LASER

LIGHT AMPLIFICATION BY STIMULATED EMISSION OF RADIATION

Topics Covered :-

→ Stimulated Absorption, Spontaneous Emission
→ Stimulated Emission
→ Einstein's Coefficients
→ Population Inversion
→ Components of Laser System
→ Principle of Laser System
→ Types of Lasers
→ Ruby Laser, Semiconductor Lasers
→ Application of Laser : Holography

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Difference between Ordinary light and Laser light

LASER	ORDINARY LIGHT
1) Laser light has a very small angular speed	1) Ordinary light has a large angular spread and spreads out in all directions.
2) Laser light is highly directional and travels in a specific direction.	

3) Laser light is highly intense

4) Laser light is coherent, all the waves are in phase and maintain a constant phase.

5) Laser is monochromatic, i.e, is of single color or wavelength.

2) Ordinary light is not directional.

3) Ordinary light is less intense since energy is distributed over a large region.

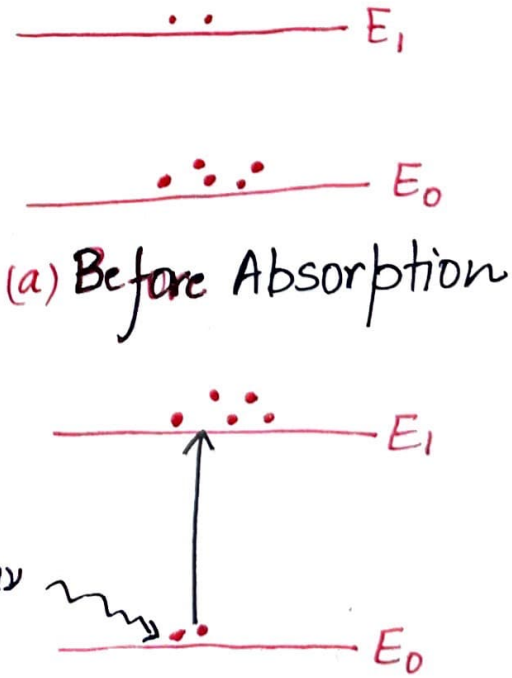
4) Ordinary light is incoherent. [Waves are not in phase]

5) Ordinary light has many wavelengths or colors.

Important interactions for LASER

① Induced Absorption

→ For an atom to go to excited state, energy is absorbed. The amount of energy absorbed is equal to energy difference between two energy levels, i.e, in this case $\Delta E = h\nu = E_1 - E_0$



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→ Photons of suitable frequency are supplied to atoms in the ground state.

→ These atoms in ground state, absorb the supplied energy and go to excited or higher state.

→ Since energy is supplied for this process to happen, it is called INDUCED and energy is absorbed by atoms in order to go to higher state, name is Induced Absorption.

→ In mathematical terms, the rate of stimulated or induced absorption can be determined. The rate (R_{ab}) depends on -

(i) (N_1), which is number of atoms in ground energy state (E_0)

$$R_{ab} \propto N_1 \quad \leftarrow (1)$$

Because, more number of atoms in ground state, more and more will absorb energy and go to higher state.

(ii) $u(\nu)$, which is the energy density of incoming photon

$$R_{ab} \propto u(\nu) \quad \leftarrow (2)$$

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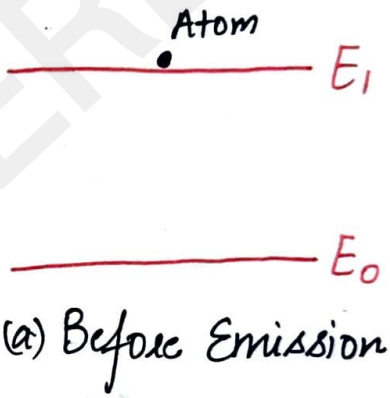
→ Now combining ① and ②

$$R_{ab} = B_{12} \cdot N_1 \cdot U(\nu) \quad \leftarrow ③$$

where B_{12} is proportionality constant and is known as Einstein's coefficient of absorption.

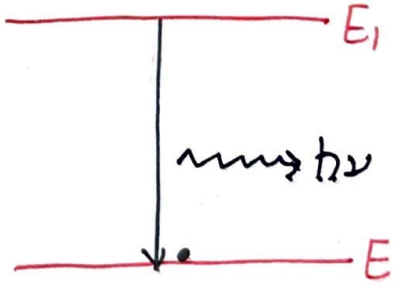
② SPONTANEOUS EMISSION

→ An excited atom can stay in higher state only for time of 10^{-8} sec. After this time, it returns to lower state.



(a) Before Emission

→ Whenever an atom comes from higher state to lower state, the energy is emitted, i.e, $\Delta E = h\nu = E_1 - E_0$. This is exactly equal to energy absorbed while atom goes from same lower to higher level.



(b) After Emission

→ Since this process happens on its own after 10^{-8} sec, it is called 'spontaneous' and because there is emission of photon, so Spontaneous Emission

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→ Mathematically, the rate of spontaneous emission depends only on (N_2), which is number of atoms in excited state.

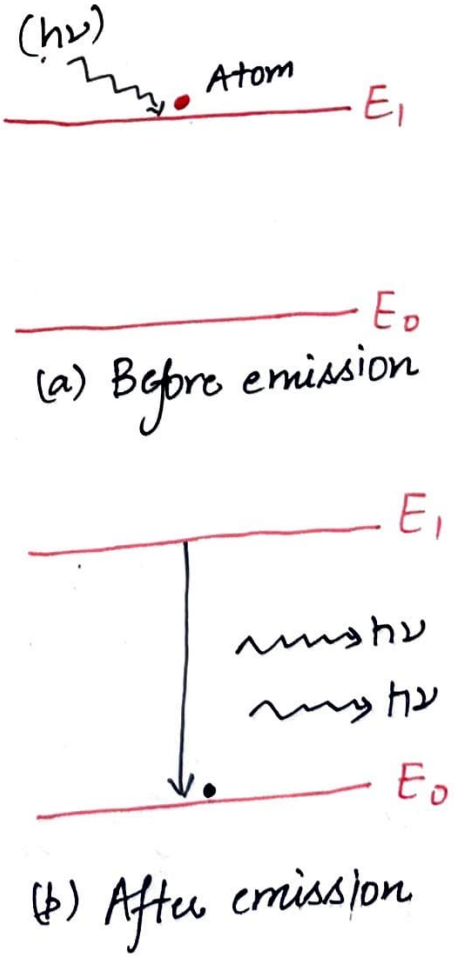
So, $$\boxed{R_{SP} \propto N_2} \leftarrow (4)$$

$$\Rightarrow \boxed{R_{SP} = A_{21} \cdot N_2} \leftarrow (5)$$

where A_{21} is proportionality constant and is known as Einstein's coefficient of spontaneous emission of radiation.

③ STIMULATED EMISSION

→ If a photon of suitable frequency, is made incident on atom in excited state having energy, $(E_0 + h\nu)$, the total energy becomes $(E_0 + h\nu + h\nu)$.



→ After having absorbed energy from incident photon, the atom falls back to ground state by emitting

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2 photons of energy $h\nu$.

→ This happens because the incident photon energy absorbed by atom makes it unstable since it has excessive energy. But this energy is not enough, that atom goes to state E_2.

→ Since the emission of photon in this process is stimulated by external photon, so the process is known as 'Stimulated Emission'.

→ This is the most important process for LASER light emission.

→ Mathematically, the rate of stimulated emission depends on –

(a) (N_2), number of atoms in excited state

$$R_{ST} \propto N_2 \quad \leftarrow (6)$$

(b) $U(\nu)$, energy density of incoming photon,

$$R_{ST} \propto U(\nu) \quad \leftarrow (7)$$

Combining (6) and (7) –

$$R_{ST} = B_{21} \cdot N_2 \cdot U(\nu) \quad \leftarrow (8)$$

where B_{21} is proportionality constant, known as

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Einstein's coefficient of stimulated emission.

Derivation of Einstein's coefficients

Under equilibrium condition, the number of transitions of atoms from lower to higher level is equal to number of transitions from higher to lower level, which implies –

$$\boxed{R_{ST} + R_{SP} = R_{ab}}$$

Substituting the values from ③, ⑤ and ⑧ →

$$B_{21} \cdot N_2 \cdot U(\nu) + A_{21} \cdot N_2 = B_{12} \cdot N_1 \cdot U(\nu)$$

$$A_{21} N_2 = B_{12} \cdot N_1 \cdot U(\nu) - B_{21} \cdot N_2 \cdot U(\nu)$$

$$A_{21} N_2 = U(\nu) \left[B_{12} \cdot N_1 - B_{21} \cdot N_2 \right]$$

$$U(\nu) = \frac{A_{21} N_2}{B_{12} \cdot N_1 - B_{21} \cdot N_2}$$

Dividing by $B_{21} N_2$ in numerator and denominator –

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$$u(\nu) = \frac{A_{21} \cdot N_2}{B_{21} \cdot N_2} \Big/ \frac{B_{12}}{B_{21}} \cdot \frac{N_1}{N_2} - \frac{B_{21} N_2}{B_{21} N_2}$$

$$u(\nu) = \frac{A_{21} / B_{21}}{\frac{B_{12}}{B_{21}} \cdot \frac{N_1}{N_2} - 1} \leftarrow (9)$$

By Boltzmann distribution equation -

$$\frac{N_1}{N_2} = e^{h\nu / k_B T}$$

So, substituting this value in (9) →

$$u(\nu) = \frac{A_{21} / B_{21}}{\frac{B_{12}}{B_{21}} e^{h\nu / k_B T} - 1} \leftarrow (10)$$

According to Planck's radiation formula for energy distribution is given by -

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$$U(\nu) = \frac{8\pi h\nu^3/c^3}{1.\, e^{h\nu/k_BT} - 1} \leftarrow (11)$$

Comparing (10) and (11), we get →

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3} \quad \leftarrow (12)$$

$$\frac{B_{21}}{B_{12}} = 1$$

$$\Rightarrow B_{12} = B_{21} \quad \leftarrow (13)$$

Significance

→ Here $\frac{A_{21}}{B_{21}} \propto \frac{8\pi h\nu^3}{c^3}$, so $B_{21} \propto \frac{1}{\nu^3}$, that means B_{21} is inversly proportional to frequency is incident radiation. Therfore, ~~the~~ higher the frequency, smaller is the value of B_{21}. So, it is comparatively difficult to obtain the stimulated emission of higher frequencies.

Condition for Amplification

We know that three rate equations are -

$$R_{ab} = N_1 B_{12} U(\nu)$$

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$$R_{SP} = N_2 A_{21}$$
$$R_{ST} = N_2 B_{21} U(\nu)$$

Now, dividing R_{ST} and R_{ab} →

$$\frac{R_{ST}}{R_{ab}} = \frac{N_2}{N_1} \quad \left[B_{21} = B_{12} \text{ from } (13) \right]$$

⇒ Stimulated Emission is the most important process for LASER, so R_{ST}, i.e, rate of stimulated emission to dominate, $N_2 > N_1$, that means number of atoms in excited energy state should be greater than number of atoms in ground state.

POPULATION INVERSION

In order to have higher rate of stimulated emission, it is important to have $N_2 > N_1$, known as population inversion.

Population Inversion is the condition in which the population of atoms is higher in an excited state than in a lower energy state.

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Mathematically it is denoted as :-

$$N_2 > N_1$$

* Population inversion in 2-level LASER

→ In a two level system, the process of absorption and stimulated emission occurs with equal probability so atoms going up and coming down balance each other.

→ As pumping increases, the populations of two levels become equal at best, but cannot be $N_2 > N_1$.

→ So, population inversion is not achievable in a two-level laser system.

* Population Inversion in 3-level LASER SYSTEM (or working of 3-level LASER)

① Normal Distribution (Absorption stage)

(i) Initially most electrons are in ground state E_1, few in E_2 and very few in E_3.

(ii) When external photons is supplied, electrons absorb energy and get excited from $E_1 \rightarrow E_3$, through stimulated absorption

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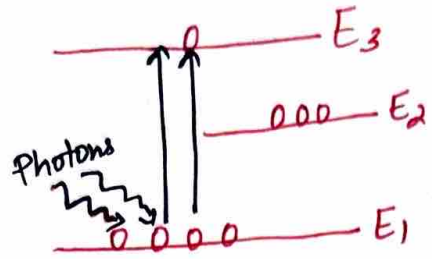
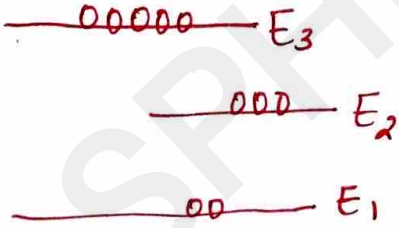


(a)

2. Pumping to higher level

(i) Continuous energy supply excites more electrons to upper energy level E_3.

(ii) The population at E_3 increases, but this state is unstable (short lifetime)



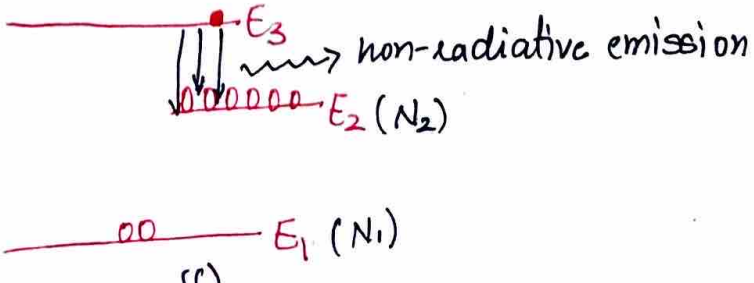
(b)

3. Non-radiative transition and population inversion

(i) Electrons quickly drop from $E_3 \rightarrow E_2$, with a non-radiative transition.

(ii) E_2 is a metastable state [having longer lifetime], so electrons accumulate there.

(iii) As a result, condition of population inversion is achieved ($N_2 > N_1$).



(c)

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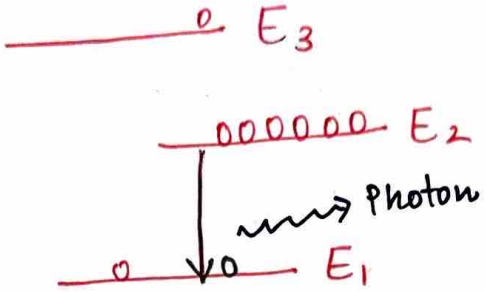
(4) Spontaneous Emission

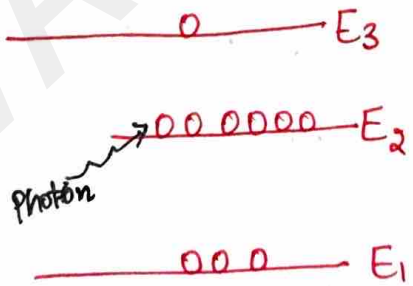
(i) Some electrons from E_2 return to E_1 on their own, emitting photons, through spontaneous emission



(d)

(5) Photon interaction

The spontaneously emitted photons travel through the medium and stimulates the excited electrons in E_2 energy level.



(e)

(6) Stimulated Emission (Laser Action)

(i) The incoming photon causes the excited electron to drop from $E_2 \longrightarrow E_1$, emitting another photon.

(ii) The emitted photons has same energy and same phase.

(iii) This process is stimulated emission, leading to

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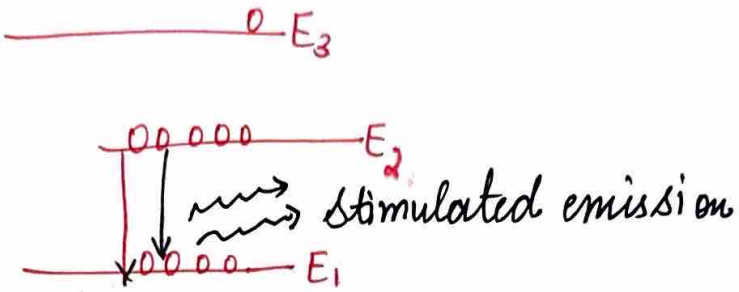
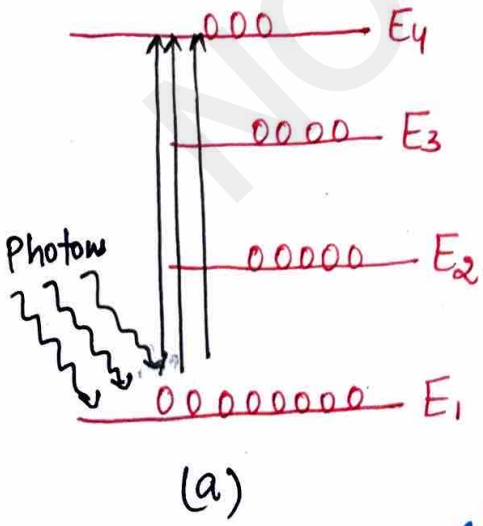
Coherent amplification of light.



Laser action occurs due to stimulated emission under population inversion, achieved via a metastable state/ stable in a 3-level system. The laser action happens in transition from $E_2 \longrightarrow E_1$ state.
[Metastable state is E_2]

Population inversion in 4-level LASER system

(Working of 4-level LASER)



(a)

1) Normal Distribution (Absorption stage)

(i) Most electrons are in ground state E_1, while a few occupy other levels.

(ii) When photons are incident, electrons absorb this energy and go from E_1 to E_4.

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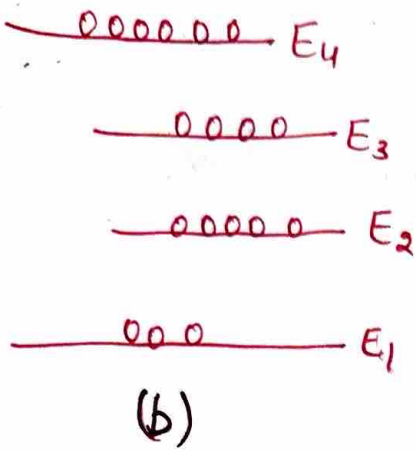
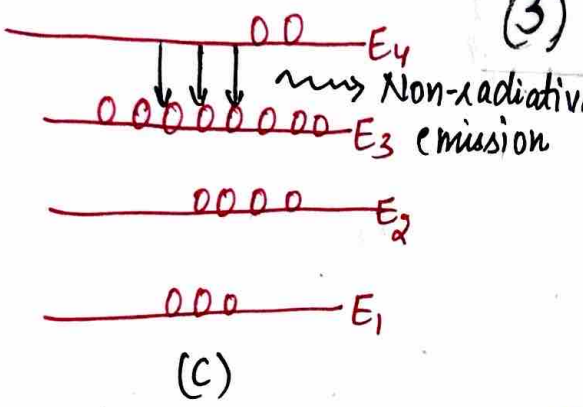


(b)

(2) Pumping to another level

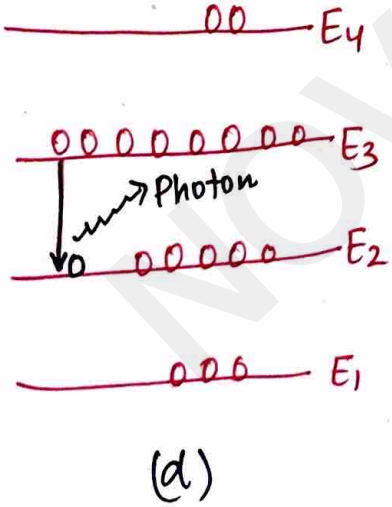
Due to continuous pumping, a large number of electrons go to highest level E_4, which is an unstable state [short lifetime]



(c)

(3) Non radiative transition

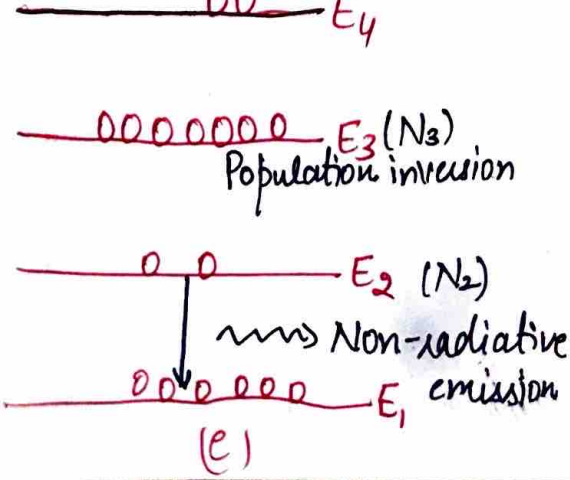
Electrons quickly drop from $E_4 \rightarrow E_3$ by non-radiative process, E_3 is a metastable state where electrons can accumulate.



(d)

(4) Spontaneous Emission

(i) Some electrons from E_3 go to E_2 by spontaneous emission, emitting photons.



(e)

(5) Population Inversion

Due to accumulation of electrons at E_3 and fast emptying of E_2 due to non-radiative emission,

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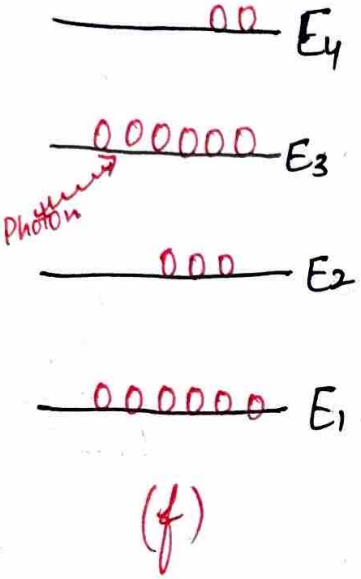
population inversion is established (E_3 and E_2, $N_3 > N_2$)

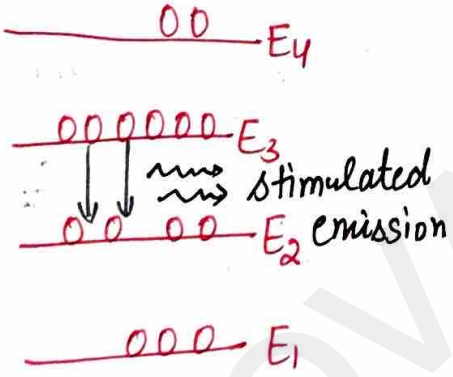


(f)

(6) Fast non radiative decay from $E_2 \rightarrow E_1$

There is non-radiative decay from $E_2 \rightarrow E_1$, which helps maintain population inversion.

The photon from spontaneous emission ($E_3 \rightarrow E_2$) stimulates excited electrons in E_3



(g)

(7) Stimulated Emission

Due to the incident photon, electrons fall from $E_3 \rightarrow E_2$ by stimulated emission and releases LASER light.

In a 4-level laser, population inversion is achieved between E_3 and E_2, where E_3 is metastable state. The LASER light is released for transition between $E_3 \rightarrow E_2$.

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COMPONENTS OF LASER SYSTEM

1) The Pump
2) Active Medium
3) Resonator

THE PUMP

→ It is an external source which supplies energy to obtain population inversion. The pump can be optical, electrical or thermal.

→ The energy supplied by the pump excites the atoms to higher energy levels and through spontaneous emission, atoms fall to metastable state.

Types of pumping :-

1) Optical Pumping :→ Atoms are excited to higher energy levels by absorbing photons from an external light source.

2) Electrical Pumping :→ Atoms are excited by energy supplied through an electric field.

3) Chemical Pumping :→ Excitation of atoms occur due to energy released during a chemical reaction.

4) Direct pumping :→ Electrical energy is directly converted into light.

Ex: In Ruby laser, we use optical pumping and He-Ne

Laser we use electrical pumping.

THE ACTIVE MEDIUM

It is the material in which the laser action is made to take place. This material can be solid, liquid or gas. The very important characteristic requirement for active medium is that it should have metastable state in order to achieve population inversion. Only few atoms are responsible for laser action and are known as active centers, while rest of material is host.

Ex: In Ruby laser, the active medium is Chromium.

THE RESONATOR

It consists of a pair of plane or spherical mirrors having common principal axis. The reflection coefficient of one of the mirrors is very near to 1 and that of other one is kept less than 1. The resonator is basically a feed-back device, that directs the photons back and forth through the laser medium and in process, number of photons is multiplied due to stimulated emission.

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Principle for Laser System

→ A laser system uses an atomic medium that contains one or more meta-stable energy states.

→ Under normal conditions, more atoms are present in the lower energy state than in the higher state.

→ To produce laser action, this normal distribution is reversed using a process called pumping.

→ Pumping creates a condition known as population inversion, where the numbr of atoms in the meta-stable state becomes greater than that in the lower energy state.

→ Atoms in the meta-stable state are relatively stable and can stay there long enough to undergo stimulated emission.

→ When a photon of suitable energy interacts with an excited atom, it stimulates the atoms to drop to a lower energy state, emitting a second photon

→ The emitted photons have same energy, phase and direction.

→ These photons are reflected back and forth inside the active medium using mirrors, causing more

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stimulated emissions.

→ This results in a chain reaction, producing a large number of identical photons.

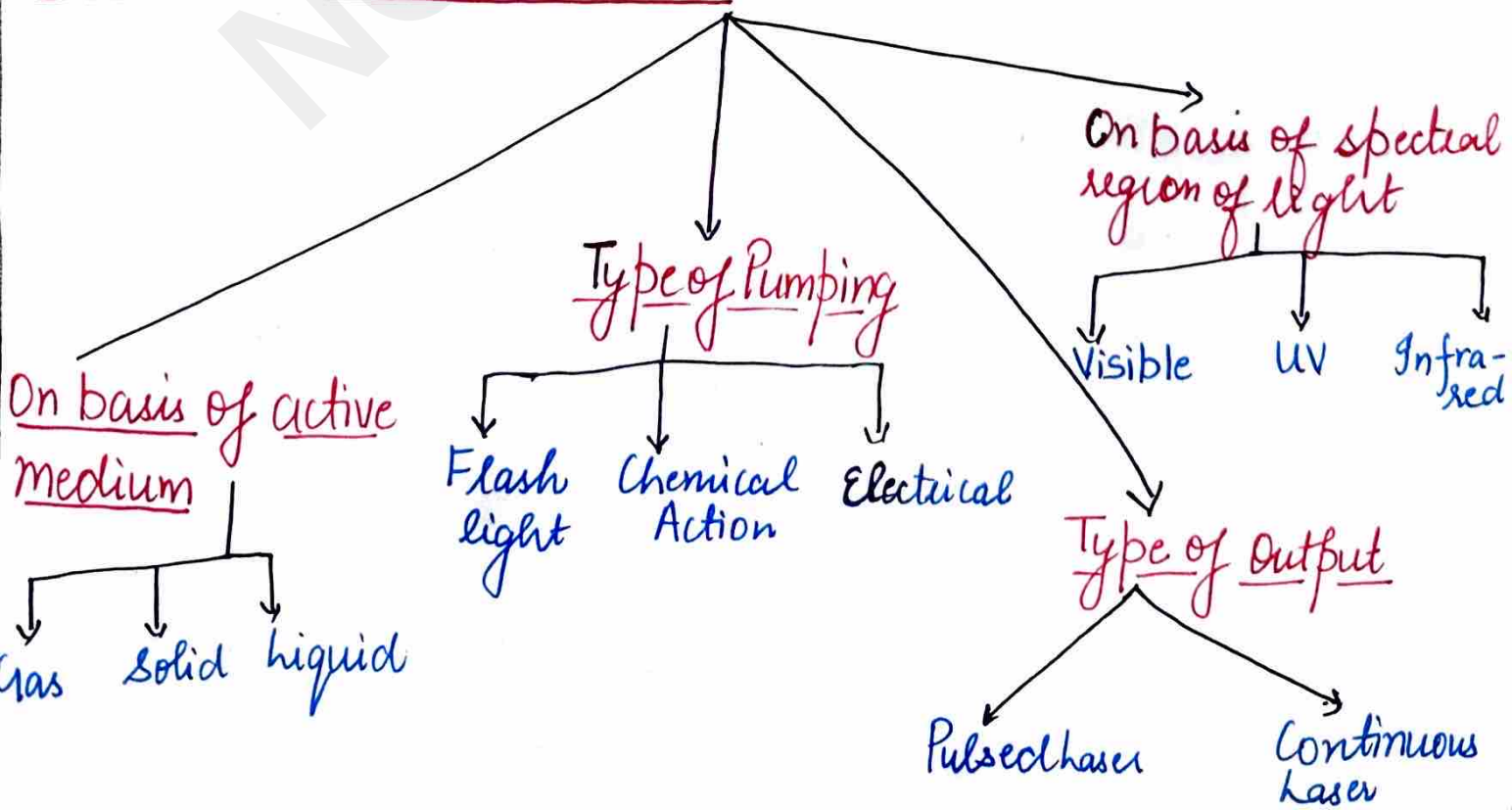
→ The process leads to amplification of light, which is basic principle of laser operation.

Conditions for LASER production

1. Population inversion condition: The number of atoms in the meta-stable state must always be greater than the number in lower energy state.

2. Stimulated Emission Condition: The emitted photons must stimulate other excited atoms, leading to multiplication of photons inside the medium.

TYPES OF LASER SYSTEM



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RUBY LASER

A ruby laser is a solid-state laser in which the active medium is a crystal of Al_2O_3 doped with Cr^{3+}. It produces a red laser light.

Principal features

→ Type : Doped Insulator Laser [3-level laser]

→ Active Medium : Aluminium Oxide + Chromium Oxide

→ Active Center : Cr^{3+} ions

→ Pumping Method : Optical Pumping

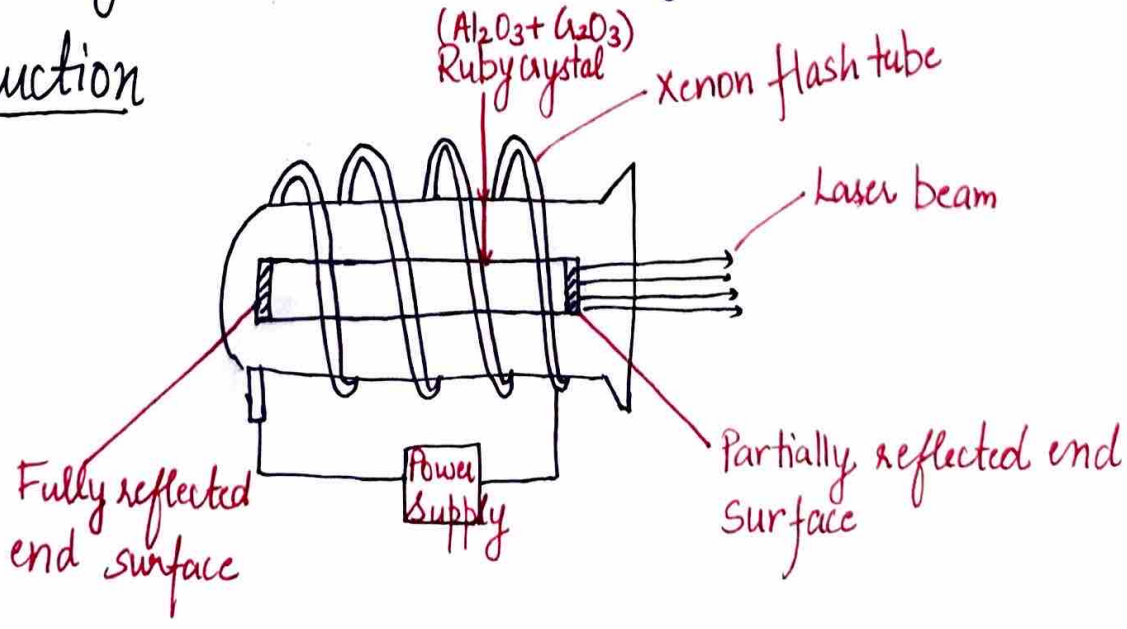
→ Pumping Source : Xenon Flash Pump

→ Resonator : Ends of ruby crystal rod which are partially and totally reflecting

→ Nature of output : Pulsed Laser

→ Wavelength : 694.3 nm (Red Color)

Construction



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→ The active medium consists of a cylindrical ruby rod made of aluminium oxide (Al_2O_3) doped with chromium ions (Cr^{3+}).

→ The ruby rod is typically about 4cm in length and 5mm in diameter.

→ The end faces of rod are optically polished and made perfectly parallel to ensure proper reflection of light inside the cavity.

→ The two ends of rods are silvered to form an optical resonator.

→ The ruby rod is surrounded by a helical xenon flash lamp, which serves as optical pumping source.

WORKING OF RUBY LASER

→ The ruby crystal is surrounded by a xenon flash lamp, which provides intense blue-green light for optical pumping.

→ The blue-green light is absorbed by Cr^{3+} ions, exciting electrons from ground state to higher energy levels.

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→ These excited electrons quickly loose energy and fall to a metastable-state through non-radiative transitions.

→ The electrons remain in the meta-stable state for some time, allowing accumulation of large number of electrons.

→ As a result, population inversion is achieved, i.e, more electrons are present in meta-stable state than in ground state.

→ When a photon of suitable energy passes through the crystal, it stimulates excited electrons to return to ground state, emitting photons.

→ The emitted photons have same frequency, phase and direction.

→ These photons reflect back and forth between two silvered ends of ruby rod, causing repeated stimulated emission.

→ This leads to multiplication of photons and amplification of light inside crystal.

→ When the intensity becomes sufficiently high, a

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strong, coherent and highly directional beam emerges from partially silvered end.

Note :→ In working of ruby laser, draw diagrams from working of 3-level laser [explained on page 6].

SEMICONDUCTOR LASER

It is a solid-state laser in which light is produced by electron-hole recombination in a p-n junction diode.

Characteristics :-

→ Type : Solid-state semiconductor laser

→ Active Medium : A p-n junction diode made from a single crystal of GaAs.

→ Pumping Method : Direct conversion method

→ Power Output : a few mW

→ Nature of Output : Continuous or pulsed

→ Wavelength : 8300 A° – 8500 A°

Construction :-

Main parts →

① P-type semiconductor layer :

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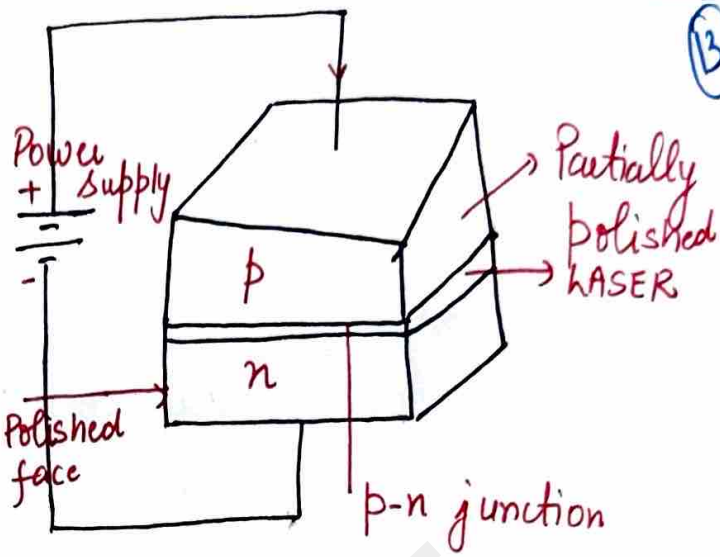
→ provides holes as majority charge carriers.



② N-type semiconductor layer:

→ Doped with donor impurities.

→ Provides electrons as majority charge carriers.

③ Active Region (brain region):

→ located at junction of p-type and n-type layers

→ This is the region where electron-hole recombination takes place, resulting in photon emission.

④ Optical Resonator:

→ The two opposite faces perpendicular to the junction plane are cleaved and polished.

→ These act as reflecting mirrors due to refractive index difference.

⑤ Electrodes:

→ The top and bottom surfaces are metalized, providing electrical contacts for applying forward bias.

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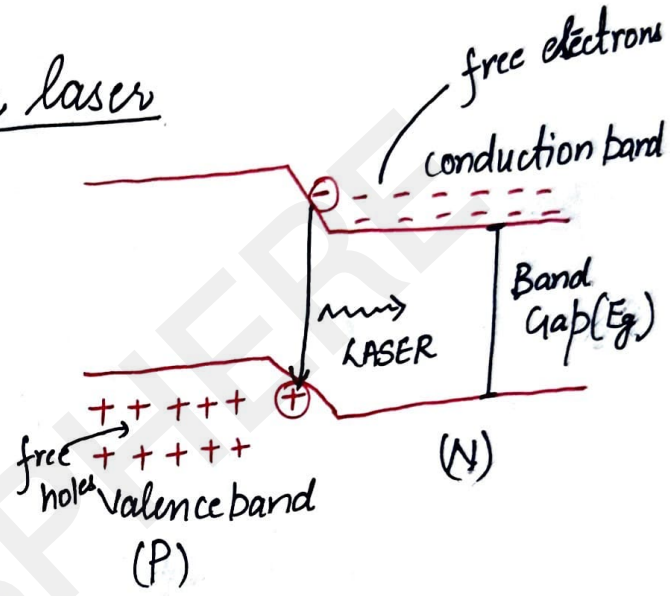
→ Forward biasing is provided as the pumping mechanism, enabling injection of electrons and holes into the active region.

Working of semiconductor laser



1) When the p-n junction is forward biased, electrons from the n-region and holes from p-region are injected into the junction.

2) The junction region thus contains a high concentration of electrons in conduction band and holes in the valence band.

3) Electrons recombine with holes, releasing energy in the form of photons.

4) As the forward bias voltage increases, more charge carriers are injected, resulting in increased photon generation.

5) At higher carrier concentration, population inversion is achieved in active region.

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⑥ The emitted photons stimulate further recombination of electrons and holes, producing more photons.

⑦ Photons travel parallel to the junction plane and are reflected back and forth between the two polished surfaces.

⑧ This repeated reflection leads to amplification of light.

⑨ When the intensity becomes sufficiently high, a coherent laser beam emerges from partially reflecting surface.

Advantages of semiconductor laser

① The laser is very small and compact.

② It has high efficency.

③ The laser output can be increased by increasing the laser current.

④ It requires very less additional equipments

⑤ It is operated with less power than ruby and CO_2 lasers.

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Applications of Laser Diode

① Widely used as light source in fiber optic communication systems due to small size, efficency and aleility to opeate at high speeds.

② Used in instruments such as range finders, optical sensors and bar code readers.

③ High power laser diodes are used in heat treatment, cladding, welding.

④ Used in laser-based medical treatments, particularly in dentistry, opthalmology and minor surgical procedures.

⑤ Used in printing industry for high-resolution printing.

Holography

Holography is the science of producing holograms. It is an advanced form of photography that allows an image to be recorded in 3d.

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Holography is a method of producing a visual three dimensional image of an object by means of light waves pattern recorded on a photographic plate.

Hologram: It is photograph of an interference pattern which when suitably illuminated by laser light, produces a three-dimensional image.

HOW TO CREATE AN HOLOGRAM

A coherent laser beam is used as light source. The laser beam is split into two parts using a beam splitter:

(i) Reference beam: Travels directly to the photographic plate without disturbance.

(ii) Object beam: Falls on the object and gets reflected onto the photographic plate.

Recording (Formation of Hologram)

→ The object beam carries information about the object after reflection.

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→ The reference beam reaches the plate directly.

→ Both beams interfere on photographic plate, producing an interference pattern.

→ The pattern is recorded on the plate, forming a hologram.

Reconstruction:

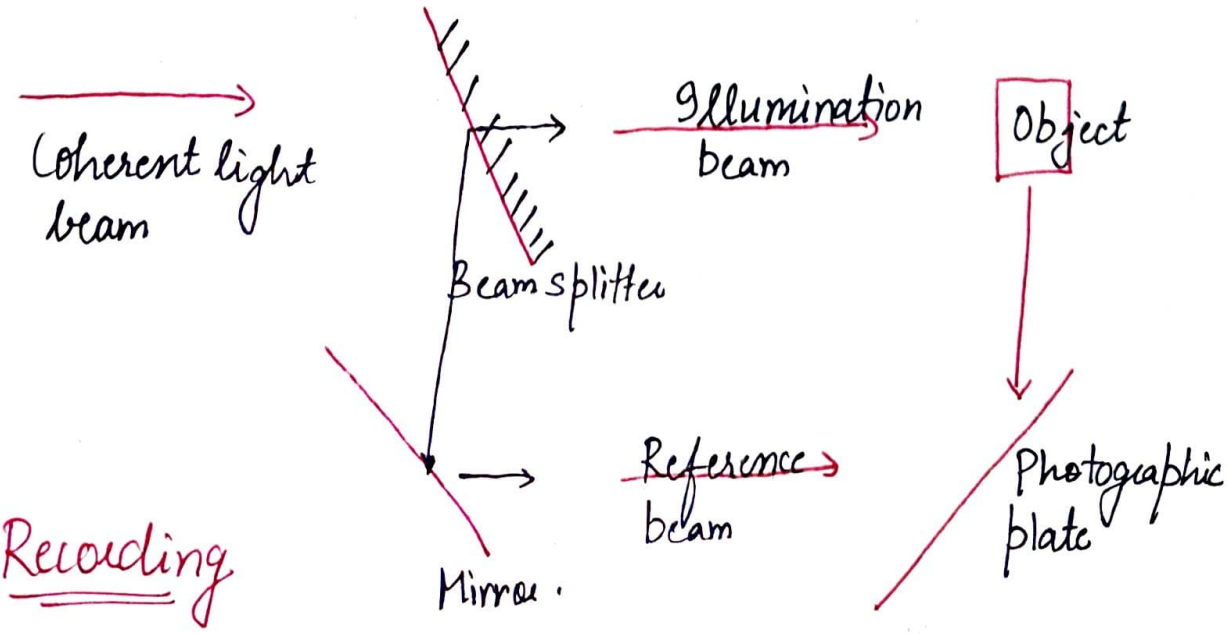
→ The developed hologram is illuminated again using the same reference beam.

→ The hologram diffracts the light, reconstructing the original wavefront.

→ A three dimensional image of object is formed:

(i) Can be virtual or real

(ii) shows depth and parallax



(a) Recording

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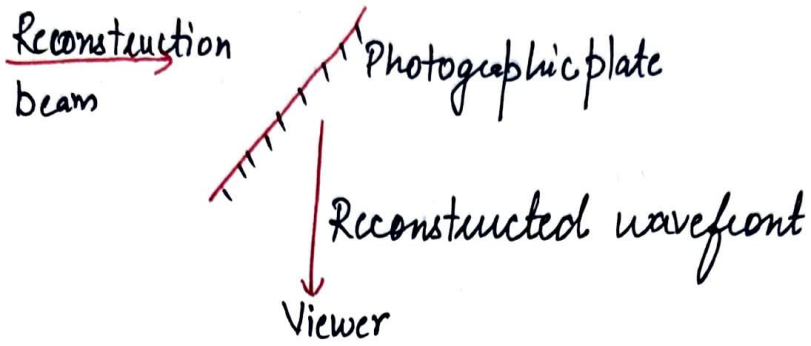
Virtual Image



(b) Reconstruction

Difference between photography and holography

Photography	Holography
① Records only amplitude of light	① Records both amplitude and phase of light.
② Produces a 2D image.	② Produces a 3D image.
③ Uses incoherent light	③ Uses coherent light.
④ Based on simple image formation by lenses	④ Based on interference and diffraction

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Applications of Holography

1. 3-D Photography: Produces true three-dimensional images with depth and parallax.
2. Bio-medical Applications: Used for 3D imaging of biological samples without damaging them.
3. Compact Disc: Uses holographic principles for high-density optical data storage.
4. Holostores: Advanced storage technique using holography for very large data capacity.
5. Holographic Scanners: Used in barcode scanners for fast and multi-angle scanning.

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